LIMNOLOGICAL STUDIES OF WESTERN LAKE ERIE

III. Phytoplankton and Physical-Chemical Data from November, 1939, to November, 1940

DAVID C. CHANDLER,
Franz Theodore Stone Laboratory,
The Ohio State University,
Put-in-Bay, Ohio

Introduction

Limnological studies of western Lake Erie, in the region of the Bass Islands, have been continuous since September, 1938, and these studies with certain modifications will be continued for several consecutive years. Results from the first year's work have been published (Chandler, 1940) and the second year's data will appear in three parts: (1) light penetration and its relation to turbidity (Chandler, 1942), (2) phytoplankton and its relation to general physical-chemical factors, and (3) seasonal and vertical distribution of zooplankton.

It is the purpose of this paper to present quantitative data showing the seasonal variation in abundance and composition of phytoplankton in western Lake Erie, and to show the relation of certain environmental factors to this plankton. Comparisons are made between data of the two years studied in an attempt to show changes in phytoplankton populations as environmental factors change. At present it is not possible to make generalizations in respect to this study, but after pursuing this plan for several years it is hoped that valuable conclusions may be forthcoming. Methods and equipment used in this investigation were essentially those used during the previous year (Chandler, 1940).

The writer is indebted to Leonard J. Bodenlos for field assistance and for chemical data.

Physical Data

Annual temperature variations of the surface water are shown in Figure 1. At the beginning of November, 1939, the surface temperature was about 9.0° C. and it declined gradually until it reached a minimum of 0.1° C. in January, 1940, shortly after the ice-cover had formed. This ice-cover attained a maximum thickness of 18 inches and covered most of western Lake Erie from January 10 to April 1. In many respects the ice-cover of the winter of 1940 was different from the ice-cover of the winter of 1939, and the possible effects of this on phytoplankton production are discussed later. Water temperature under this ice-cover did not exceed 1.5° C., but it increased gradually with the disappearance of the ice-cover, until a maximum temperature of 25.0° C. was reached in mid-August. Following this maximum the temperature descreased gradually until it reached 11.8° C. in late October, a temperature similar to that of late October, 1939.

Water temperature was quite uniform vertically on a given date, except on three occasions. On May 14, June 5, and June 11, temporary thermoclines were formed, but each was destroyed a few days later by wind action. These thermoclines varied from 1 to 3 m. in thickness and they occurred at various depths from 2 to 8 m. Since these periods of thermal stratification were brief and irregular, and produced small vertical changes in chemical values, we are justified in assuming that thermal stratification is of little importance in this region. Likewise, temperature conditions of the surface water are quite representative of temperature conditions at other depths.

Data pertaining to turbidity and transparency in western Lake Erie from November, 1939, to November, 1940, have been published (Chandler, 1942); therefore, general statements concerning these factors will suffice in the present paper. Curves of turbidity values and Secchi's disc readings are presented in Figure 1. Turbidity values varied from a minimum of 5 ppm., during most of January, February, early March, and for two weeks in June, to a maximum of 60 ppm. in late June. From June to October turbidity at no time was less than 20 ppm.; the average was much higher than for the corresponding period of the preceding year. This turbidity is caused in part by disturbance of bottom sediments through wind action. During this particular year turbidity was highest in summer and autumn, and lowest in winter and spring, but the preceding year was characterized by high turbidity in spring and autumn, and low turbidity during winter and summer.

Chemical Data

Chemical analyses were made at surface, 5 m., and 9 m. as a regular routine, and analyses at intermediate depths were made when chemical values showed definite vertical variations. In most instances chemical values were nearly uniform vertically; therefore, the graphs for surface values (Fig. 1) give general information concerning chemical conditions from top to bottom on a given date, as well as showing seasonal trends.

Dissolved oxygen in the surface water varied from a maximum of 13.2 ppm. on several occasions in April and May, to a minimum of 7.8 ppm. in August. The oxygen content of the water was high during autumn, winter and spring, and low in summer, as might be expected from data on abundance of phytoplankton (Fig. 2) and on temperature (Fig. 1). Weekly fluctuations in oxygen content during periods of open water were probably due largely to agitation through wave action, but the variations which occurred while an ice-cover was present were probably due to currents. Currents, which are known to exist under the ice, may have moved water with a different oxygen content into the area investigated, or these currents may have increased the turbidity through agitation of bottom sediments which in turn affected the quantity of oxygen. On December 12, 1939, March 29, and June 22, 1940, high turbidity was associated with low oxygen content. It is likely that the organic sediments present during high turbidity consume oxygen while the inorganic components adsorb oxygen. Vertical distribution of oxygen was not uniform on a given date, but it rarely varied more than 2 ppm. from top to bottom, and often it varied less than 1 ppm. The most pronounced vertical variation occurred on June 11, 1940, at which time a thermocline existed. On this date the oxygen content was above 9 ppm. at surface and 5 m., but at 9 m. it was only 6.5 ppm.; however, a few days later vertical distribution was nearly uniform again.

The pH varied from a minimum of 7.4 in February to a maximum of 8.4 in May, 1940. The graph of surface values in Figure 1 shows that pH was less than 8.0 from early November, 1939, to early May, 1940, and it was 8.0 or more from mid-May to November, 1940. Seasonal changes in pH were similar for the two years of investigation and vertical variation was small except on a few occasions when temporary thermoclines existed.

Free carbon dioxide, from November, 1939, to late April, 1940, was present in quantities varying from 0.5 to 4.2 ppm., and from May until mid-October it was absent except for two collection dates in June and July. From mid-October to November, 1940, free carbon dioxide did not exceed 0.5 ppm., but it was always present. A storm in late June and early July agitated the water from top to bottom, causing bottom sediments to be thrown into suspension; this resulted in a sudden rise in free CO_2 (Fig. 1) as is typical of such disturbances. Data for the present year are similar to those of the preceding year, except that in the former year considerable free CO_2 was present during the entire month of November, while in the latter year it was absent during November. This difference is probably associated with the decomposition of the autumn plankton pulses which were very different in size in the two years. No significant difference in vertical distribution of CO_2 occurred except on July 2, when the surface determination was 0.0, and at 5 and 9 m. the values were 1.0 and 2.0 ppm., respectively.

Methyl orange alkalinity of the surface water varied from 84.0 to 92.0 ppm. from November, 1939, to late April, 1940, and it was less than 84.0 ppm. from late April to June, except on May 14 and 21 (Fig. 1). From June to November, 1940, methyl orange values ranged from 83.0 to 94.0 ppm. The seasonal variation in this factor was approximately the same for the two years of investigation, and vertical variation on a given date was not greater than 2 ppm., except for two collections in March. These differences were probably caused by melted ice and snow running into the open hole through which water samples were taken.

Ph-th alkalinity values for the surface water (Fig. 1) were 0.0 from November, 1939, to the second week in May, 1940. From mid-May until mid-October these values were irregular from week to week ranging from 0.0 to 5.3 ppm., and during late October the values returned to 0.0. The relationship of Ph-th alkalinity to free CO_2 is shown graphically in Figure 1.

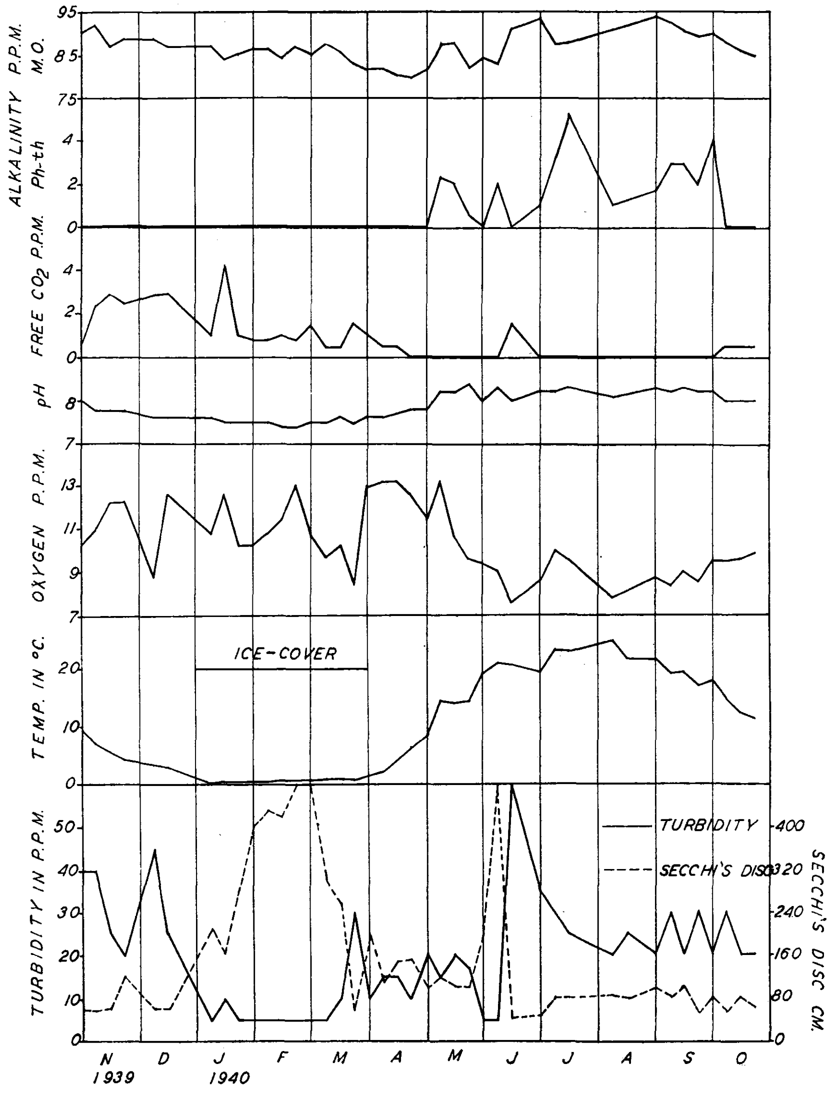

FIG. 1. Values in the upper meter of water for methyl orange alkalinity, ph-th alkalinity, free carbon dioxide, pH, dissolved oxygen, temperature and turbidity. Secchi's disc readings are given in meters.

Phytoplankton Data

Seasonal Distribution

Total Phytoplankton

Data concerning seasonal distribution and relative abundance of phytoplankton refer to the standing crop, which was determined by averaging data from collections at surface, 5 m., and 9 m. for a given date. Plankton collections during the present year were made in the same area as those of the preceding year.

Quantitative data pertaining to the standing crop of phytoplankton are shown in Figure 2. Examination of these data shows that in early November, 1939, the quantity was 135,000 units per liter, and following this the quantity decreased gradually until the winter minimum of 7,000 units per liter was reached in January, 1940. Through January and February the quantity was 20,000 units per liter or less, but in early March a sudden increase occurred resulting in 78,000 units per liter by March 21. The following week was characterized by a sudden decrease in abundance of phytoplankton, accompanied by a sudden increase in turbidity. By April the turbidity had decreased considerably and the abundance of phytoplankton had begun to increase; it reached a spring maximum of 374,000 units per liter on May 7. This pulse decreased rapidly until a summer minimum of 8,000 units per liter was attained June 22, at which time high turbidity prevailed. From late June to late August less than 32,000 units per liter were present, but in late August the autumn pulse began and it increased gradually until a maximum of 97,000 units per liter occurred in late September. In October the quantity decreased gradually and by late October only 13,000 units per liter existed. On the whole, the spring pulse of 1940 was distinct and of expected proportions, but the autumn pulse was considerably smaller than the two preceding autumn pulses. This autumn pulse was not only small, but it appeared in two phases, the second part appearing three weeks later than the first. The writer had assembled data for this paper at the termination of the first phase, consequently the second phase has been omitted from this report, except for general data in the discussion.

The following section of this paper gives the salient facts concerning seasonal trends in abundance of the major phytoplankton groups and the predominant genera composing these groups. Species will not be discussed because of the difficulty in recognizing them while making the quantitative counts. A list of phytoplankton species occurring in western Lake Erie, exclusive of diatoms, has been published by Tiffany (1934).

Myxophyceae

Blue-green algae were important constituents of the plankton only during summer and autumn, and in this investigation only 12 genera were encountered in sufficient numbers to be considered important quantitatively. In early November, 1939, blue-greens were present in quantities of 22,000 units per liter, this being the declining portion of a large pulse with a maximum of 210,000 units per liter that occurred in September and October, 1939. By late November members of this group were nearly absent from the plankton, and they remained at a

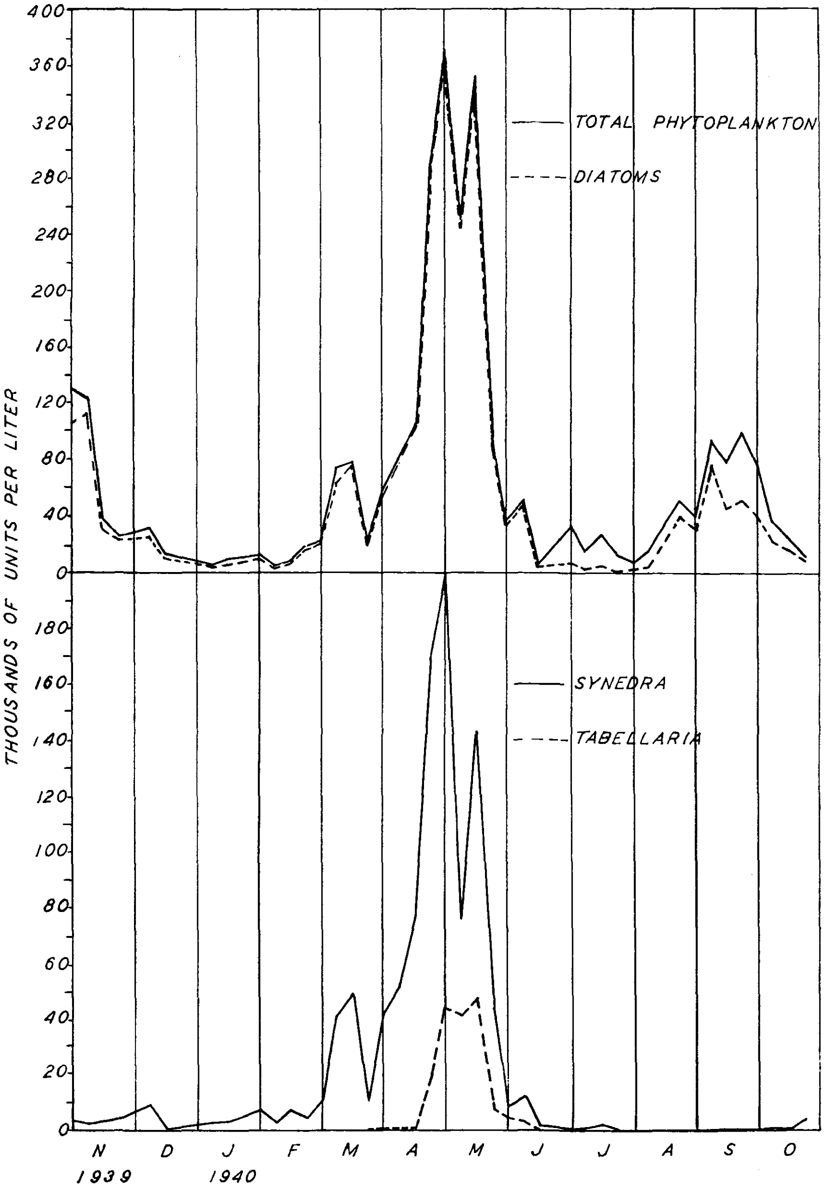

FIG. 2. Standing crop of total phytoplankton, total diatoms, *Synedra*, and *Tabellaria*, in thousands of units per liter.

low level until April, 1940, when they appeared in quantities of 5,000 units per liter (Fig. 3). From March to September blue-greens varied from a maximum of 12,000 units per liter in mid-July to only a few hundred units per liter in June and August. In early September blue-greens increased in abundance and a pulse with a maximum of 40,000 units per liter had occurred by late September. Following this maximum the quantity decreased rapidly until no more than 1,000 units per liter were present by late October, 1940. In general, the periods of maximum abundance of this group occurred at approximately the same times in each of the two years of investigation, but the autumn pulse of 1939 was several times larger than those in 1938 and 1940.

Anabaena occurred from September to mid-October, 1940, in quantities not exceeding 1,500 units per liter.

Aphanizomenon and *Oscillatoria* were combined in making quantitative counts because of the difficulty involved in always distinguishing them under low magnification. These genera were present in all November collections of 1939, but the quantities varied from 18,000 units per liter during the early part of the month to a few hundred units per liter at the end of the month. From December, 1939, to May, 1940, these forms were scarce, but from early May to early June they occurred in quantities of 3,000 units or less per liter. During most of June and July they were present in small quantities, but during August they increased gradually until they reached a maximum of 26,000 units per liter in late September. Following this maximum they declined and by late October the number was reduced to 1,000 units per liter. These genera were most abundant from mid-August to mid-October, but for the three autumns of study considerable variation in quantity occurred. The maxima are as follows: 1938, 8,000 units per liter in September; 1939, 104,000 units per liter in late September; 1940, 26,000 units per liter in late September. Since these two genera constitute a large percentage of the total Myxophyceae these annual variations are of considerable importance.

Aphanocapsa was present in collections from mid-August to mid-September, but the quantity did not exceed 1,000 units per liter.

Aphanothece occurred in collections during July and August, but in quantities of 1,500 units or less per liter.

Chroococcus was absent from collections made from November, 1939, to May, 1940. It reached a maximum of 4,000 units per liter in July, and attained a second peak of abundance of 5,000 units per liter in October.

Coelosphaerium was found in quantities of less than 800 units per liter from November, 1939, to August, 1940. During September and October a pulse appeared with a maximum of 14,000 units per liter and by late October this form had decreased to 700 units per liter.

Gloeotrichia was present in late July and August, but it did not exceed 1,000 units per liter.

Gomphosphaeria occurred only in August and September collections and the quantity did not exceed 1,000 units per liter.

Merismopedia was absent from all collections from November, 1939, to September, 1940, except for one sample in July. A small pulse occurred during September and October with a maximum of 1,300 units per liter.

Microcystis was absent from the plankton between November, 1939, and July, 1940. It was present in all collections from July to late October, and the maximum abundance of 4,000 units per liter occurred in late August.

Chrysophyceae

Dinobryon occurred from January through May, 1940, but at no time did it exceed 1,300 units per liter.

Mallomonas was present in three collections during May and June, but in amounts less than 1,200 units per liter.

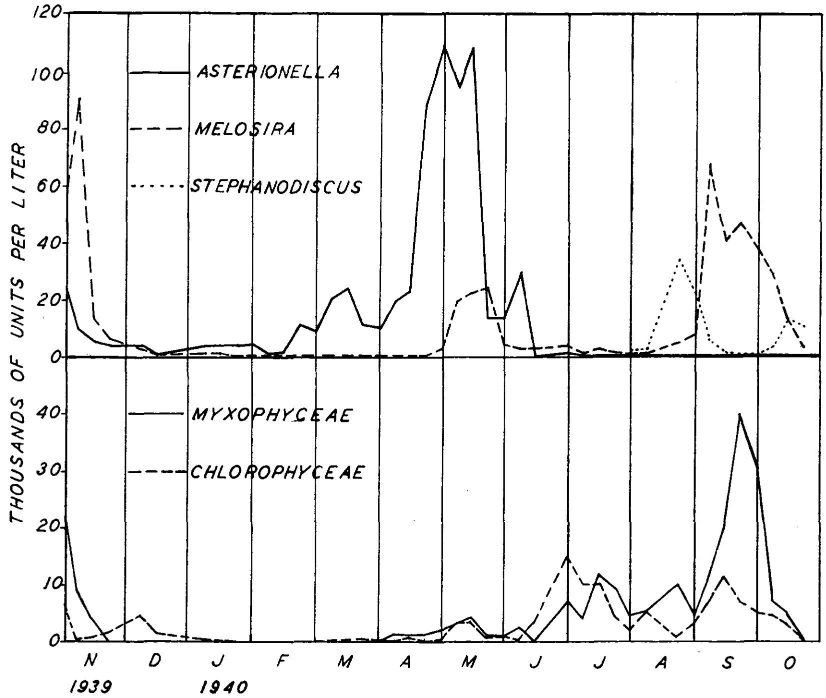

FIG. 3. Standing crop of *Asterionella, Melosira, Stephanodiscus,* total Myxophyceae, and total Chlorophyceae in thousands of units per liter.

Heterophyceae

Botryococcus was found in several collections during August and September, but never in numbers greater than 2,000 units per liter.

Tribonema occurred during August and September in quantities less than 1,000 units per liter.

Bacillariophyceae

Diatoms were present in all collections and in most instances they constituted the major portion of each collection. This is borne out by Figure 2 which shows that the curve for seasonal abundance of diatoms resembles very closely the curve for seasonal abundance of total phytoplankton. In early November, 1939, the quantity of diatoms was 106,000 units per liter; this represents the declining part of a pulse with a maximum of 175,000 units per liter that occurred from late August to late October, 1939. Diatoms decreased in quantity through November and December, 1939, and in January, 1940, they reached a winter minimum of 8,000 units per liter. Through January and February, 1940, diatoms did not exceed 20,000 units per liter, but in early March they increased in number, and by mid-March a quantity of 78,000 units per liter was present. This quantity decreased abruptly the following week to 21,000 units per liter, following which the abundance increased gradually, and then more rapidly through April to the spring maximum of 371,000 units per liter in early May. By late May this pulse had begun a rapid decline until in late June less than 10,000 units per liter were present, and the population was further decreased to a summer minimum of 1,400 units per liter in late July. Following this minimum the number of diatoms gradually increased, and produced the autumn pulse which had its maximum of 75,000 units per liter in mid-September. Through late September and early October diatoms decreased in quantity and by November, 1940, only 11,000 units per liter were present. The most conspicuous feature in respect to seasonal abundance of diatoms during this year is the unusually small autumn pulse of 1940.

Amphiprora occurred only in April and May collections, and it did not exceed 1,200 units per liter.

Asterionella was present in all collections except those made in August, September, and October, 1940 (Fig. 3). In early November, 1939, this form was present in quantities of 23,000 units per liter, but it decreased rapidly and remained below 4,000 units per liter from late November, 1939, to mid-February, 1940. It increased in abundance in late February, and continued increasing with certain irregularities to the spring maximum of 108,000 units per liter in early May. The pulse decreased through May and June, and from July to October this form when present did not exceed 700 units per liter. This plankter had one distinct pulse and that occurred in spring, as it did the preceding year. However, in 1939 the spring pulse was larger, and it occurred during February, March, and early April.

Cyclotella occurred in collections of November and December, 1939, with a maximum of 10,000 units per liter, but it was absent in collections made from January to April, 1940. A pulse occurred from mid-April to July, and the maximum of 9,000 units per liter appeared in late May. It was present in collections from late July to November, but it did not exceed 4,000 units per liter.

Cymatopleura was found in collections of November, 1939, September and October, 1940, but it did not exceed 1,500 units per liter.

Cymbella appeared in April and May collections, but it did not exceed 1,200 units per liter.

Diatoma was present occasionally in collections made from November, 1939, to March, 1940, but not in amounts over 1,200 units per liter.

Fragilaria occurred in all collections from November, 1939, to November, 1940, except for the collections of July, August and September. In early November, 1939, the quantity was 4,000 units per liter, but by late November it had decreased to 1,000 units per liter and it maintained this level to mid-April, 1940. A pulse extended from mid-April to June, the maximum being 9,500 units per liter in early May. In October it appeared in quantities not exceeding 1,000 units per liter.

Gomphonema was present in several collections during November, 1939, September and October, 1940, but it did not exceed 1,200 units per liter at any time.

Gyrosigma occurred from November, 1939, to February, 1940; the maximum for the period was 3,500 units per liter.

Melosira occurred in nearly every collection made from November, 1939, to November, 1940, but pulses occurred in autumn and spring (Fig. 3). In early November, 1939, the quantity of this form was 91,000 units per liter; this was the decreasing phase of a large pulse that occurred in late October. From December, 1939, to May, 1940, it was present in numbers less than 1,500 units per liter. A small pulse, with a maximum of 25,000 units per liter, extended from May to early June. From June to September quantities less than 5,000 units per liter were present, but from September to November a pulse occurred with a maximum of 68,000 units per liter.

Navicula was present in most collections, but it did not exceed 1,600 units per liter.

Rhizosolenia occurred from November, 1939, to early February, 1940, in quantities less than 2,300 units per liter. It was absent from collections made from mid-February to mid-June, but from mid-June to early July a small pulse appeared with a maximum of 3,500 units per liter. Due to the fact that this plankter is translucent it is extremely difficult to make accurate counts during periods of high turbidity. Therefore, the abundance of this form may be very different than indicated here.

Stephanodiscus was present in quantities exceeding 700 units per liter only during the autumn of 1940 (Fig. 3). In August and September a pulse occurred with a maximum of 34,000 units per liter, and in October a secondary pulse appeared with a maximum of 13,000 units per liter. This plankter is of particular interest because in the autumn of 1938 it appeared in a large pulse, the maximum being 251,000 units per liter, and it constituted about 95 per cent of the total phytoplankton at this time. Since 1938 it has not appeared in quantities exceeding 34,000 units per liter.

Surirella occurred in collections during November, 1939, in quantities less than 1,000 units per liter, and in May, 1940, a small pulse appeared with a maximum of 4,700 units per liter.

Synedra was present in all collections from November, 1939, to March, 1940, but at no time did it exceed 10,000 units per liter (Fig. 2).

In early March it increased rapidly to 48,000 units per liter, and then dropped to 11,000 units per liter on March 29, at which time turbidity rose suddenly from 5 to 30 ppm. In early April this form began a rapid increase, and it continued to do so until the spring maximum of 202,000 units per liter was reached in early May. Following this maximum the quantity decreased rapidly, and by late July it was scarce. From August to November, 1940, it was absent except for the last collection in October. This plankter, along with *Asterionella,* composed over 90 per cent of the entire spring diatom pulse. The spring pulse of 1939 occurred in February and March, and its maximum was only 48,000 units per liter.

Tabellaria had but one pulse and that occurred from April to mid-June, 1940, the maximum being 47,000 units per liter (Fig. 2). During the rest of the year it was absent or when present it did not exceed 1,200 units per liter.

Chlorophyceae

Green algae composed only a small percentage of the total phytoplankton during this year, and only in summer and autumn were these forms sufficiently abundant to be of quantitative importance (Fig. 3). From early November, 1939, to mid-June, 1940, green algae when present did not exceed 3,000 units per liter, except on two occasions. These exceptions occurred in November and December, 1939, at which time the quantity was 7,000 and 4,500 units per liter respectively. In late June, 1940, this group increased in quantity and formed a small pulse that extended to mid-August; the maximum was 15,000 units per liter. A second pulse, with a maximum of 12,000 units per liter, extended from September to mid-October. In many respects the abundance of green algae in the plankton was very similar for the autumns of 1938 and 1940, but it was more than twice as abundant in the autumn of 1939 than in either of the autumns of 1938 or 1940.

Actinastrum occurred only during September, 1940, in quantities not greater than 1,200 units per liter.

Ankistrodesmus was present in a few collections from mid-April to mid-June, 1940, but it did not exceed 600 units per liter.

Closteriopsis was found in three collections in July, 1940, but it did not exceed 1,200 units per liter.

Closterium was present in four collections in late summer, but the quantity was less than 1,200 units per liter.

Coelastrum was absent from the plankton from November, 1939, to mid-July, 1940. The maximum abundance from July to late October was 1,700 units per liter.

Crucigenia occurred in two collections in September, 1940, and the greatest quantity was 1,200 units per liter.

Dictyosphaerium occurred in collections in November, 1939, with a maximum of 5,600 units per liter. This quantity represented the declining phase of a pulse, with a maximum of 32,000 units per liter that occurred in September and October, 1939. It was absent from December, 1939, to September, 1940, except for a few collections in

July and August, at which time only an occasional individual was encountered. During September and October, a small pulse appeared, reaching a maximum of 6,400 units per liter in late September.

Kirchneriella occurred infrequently in June, July, and August collections, and it did not exceed 700 units per liter.

Oöcystis was absent from collections made from November, 1939, to late June, 1940. From late June to November, 1940, it occurred in most collections, but in numbers less than 1,000 units per liter.

Pediastrum occurred in quantities not exceeding 1,200 units per liter in November, 1939, and it was absent from December, 1939, to June, 1940. It was present in nearly all collections from June to November, 1940, but it was so irregular in quantity that nothing comparable to a pulse appeared. The greatest abundance occurred in early July, and it was 3,300 units per liter.

Quadrigula was present in most collections from late March to early July, and the maximum quantity encountered was 1,200 units per liter in July.

Scenedesmus occurred in most collections in November and December, 1939, but it did not exceed 1,000 units per liter. It was absent from collections from January to May, 1940, but it was present in most collections from May to October. During this latter period it was most abundant in May, June, and July, reaching a maximum of 2,300 units per liter in May.

Schroederia was absent from all collections made from November, 1939, to July, 1940. From July to November it was present in most collections and a distinct pulse occurred from July to September; a maximum of 6.400 units per liter occurred in July.

Selenastrum was found in collections of September, 1940, in quantities less than 1,200 units per liter.

Sorastrum occurred in August and September, 1940, in numbers no greater than 1,500 units per liter.

Staurastrum was present in collections made in July, August, and September, 1940, but it did not exceed 1,500 units per liter.

Westella was found in June, July, and August, 1940, but in quantities less than 1,200 units per liter.

Percentage Composition

Composition of the phytoplankton of individual collections, based on percentages that each component group constituted of the total, is shown in Figure 4. The more important facts concerning the composition of this phytoplankton may be summarized by the following statements. (1) Diatoms constituted approximately 85 per cent during November and December, 1939; about 95 per cent from January to late June, 1940; 10 to 33 per cent from late June to mid-August; 80 per cent from mid-August to early September; and 50 to 68 per cent from early September to late October. (2) Blue-greens made up 8 to 15 per cent of the total during November, 1939; less than 5 per cent from December, 1939, to July, 1940; 20 to 60 per cent during July, August, and most of September and October. (3) Greens composed from 2 to 15 per cent of the total phytoplankton during November and December, 1939; less than 3 per cent from January to late June, 1940; 25 to 60 per cent from late June to mid-August; and 4 to 17 per cent from September to late October. (4) Plankton algae, exclusive of the three groups listed above, designated as miscellaneous in Figure 4, composed less than 5 per cent of any collection made during the period of investigation. Composition of the phytoplankton from September, 1938, to November, 1939, was quite different from that of the period November, 1939, to November, 1940, and these major differences are considered in the discussion of this paper.

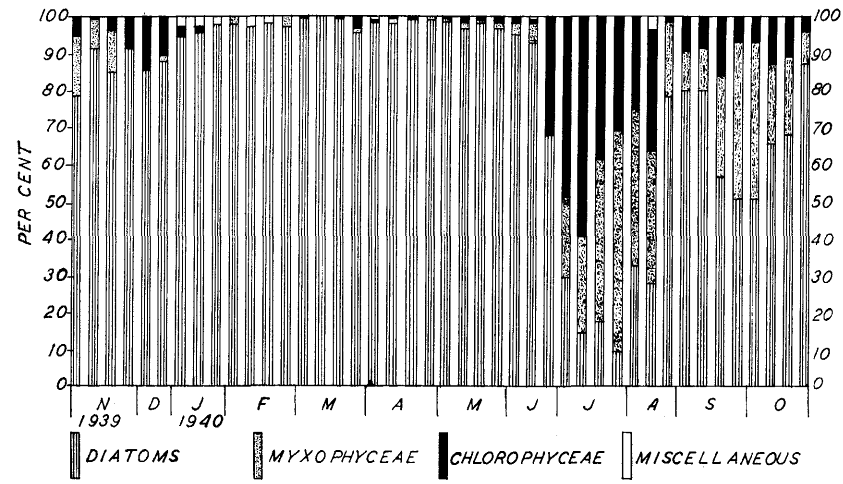

FIG. 4. Per cent composition of phytoplankton for individual collections.

VERTICAL DISTRIBUTION

Quantitative differences in phytoplankton at various depths in western Lake Erie occur, but these differences are so irregular that no one depth has consistently a greater abundance than others. At times the greatest quantity occurs at the surface, while at other times it is most abundant at 5 m., and still at other times it is most abundant at 9 m. Likewise, the qualitative difference of phytoplankton at various depths is so irregular throughout the year that no consistent trend can be discerned. The explanation for this irregularity in the vertical distribution of the quality and quantity of phytoplankton lies in the fact that the shallow water of western Lake Erie is circulated frequently from top to bottom by wind action. It is possible that at times of temporary thermal and chemical stratification the vertical distribution of phytoplankton conforms to a regular pattern; however, thermal stratification in this end of the lake is limited to only a few days each year. Because vertical distribution of phytoplankton is so irregular in this region it has seemed advisable to discuss phytoplankton data in terms of standing crop.

Discussion

The following discussion points out the salient facts concerning the seasonal variation in abundance and composition of the phytoplankton in western Lake Erie, from November, 1939, to November, 1940, and shows how this plankton differs from the plankton of the preceding year. Turbidity is discussed as a factor that may exert considerable influence upon the phytoplankton populations in this area.

In general the physical-chemical factors of the water of western Lake Erie, for the present year (November, 1939, to November, 1940) are very similar to those of the preceding year. However, certain differences exist and these may be summarized. (1) Air temperature from January to April, 1940, was considerably lower than for the same period of the preceding year. During the winter of 1940 the ice-cover was about 16 inches in thickness and it covered the entire western end of the lake, while in 1939 the ice-cover did not exceed 8 inches in thickness and it was confined to the immediate region of the Bass Islands. This difference in extent of ice-cover for the two years had little differential effect on the water temperature. (2) Thermal stratification during both years was limited to a few days in May and June. (3) Turbidity during the winter of 1940 was lower than for the winter of 1939. This difference for the two winters may be explained by the fact that the limited ice-cover of 1939 exposed more water to agitation by wind, while the extensive ice-cover of 1940 protected most of the water of western Lake Erie from wind. (4) Depths to which 1 per cent of the surface light penetrated for the two years bear an inverse relationship to turbidity; consequently, during the seasons of low turbidity light penetrated to greater depths than when turbidity was high. (5) Likewise, Secchi's disc readings for the two years varied inversely with the degree of turbidity. (6) Such factors as dissolved oxygen, pH, alkalinity, and free carbon dioxide differed for corresponding times during the two years, but the writer hesitates at this time to state either the reason for or the importance of these variations.

Phytoplankton pulses occurred in the autumn of 1939, only the latter portion of which is treated in this paper, and in the spring and autumn of 1940. These pulses differed from each other in several respects and from those reported for the preceding year. The declining portion of the autumn pulse of 1939 was composed primarily of *Melosira* and *Asterionella* (Fig. 3), and the period was characterized by turbidities varying from 20 to 40 ppm. The spring pulse of 1940 occurred from mid-March to late May, reaching a maximum of 374,000 units per liter in early May. Diatoms composed 98 per cent of the total phytoplankton and the remaining 2 per cent was divided equally between green and blue-green algae. *Synedra* and *Asterionella* were the dominant forms, but *Tabellaria, Fragilaria,* and *Melosira* contributed substantially to the plankton. This pulse began while the ice-cover was still present, but not until the ice-cover had disappeared did the pulse increase rapidly to its maximum. Average turbidity for the three weeks preceding and during the pulse was 15 ppm., a relatively low turbidity for this body of water. Water temperature varied from 0.8° C. to 14.6° C. during the pulse and the maximum abundance of plankton occurred at a temperature of 8.0° C.

TABLE I

Summary data pertaining to phytoplankton pulses in respect to the following: time of occurrence; duration; average, and maximum number of phytoplankters per liter; composition; average turbidity 3 weeks preceding, and during the pulses; and water temperature during the pulses. Each of the two parts of the 1940 autumn pulse has been treated separately, as well as in combined form.

Time of Pulse	Pulse Duration in Weeks	Av. No. Plankters per Liter	Max. No. Plankters per Liter	Av. Turb. During Pulse	Av. Turb. 3 Weeks Preceding Pulse	Water Temp. °C. During Pulse	Percentage Composition		
							Diatoms	Blue-Greens	Greens
Sept. 2–Nov. 5, 1938	9	159,000	330,000	30 ppm.	30 ppm.	23.0–12.0	84	9	6
Feb. 25–April 11, 1939	6	153,000	247,000	42 ppm.	18 ppm.	0.1– 3.2	96	3	1
July 22–Nov. 9, 1939	16	205,000	320,000	23 ppm.	16 ppm.	23.0– 7.4	48	39	12
March 14–May 28, 1940	11	160,900	374,000	15 ppm.	5 ppm.	0.8–14.6	98	1	1
Sept. 13–Nov. 29, 1940	8	85,500	111,000	55 ppm.	23 ppm.	19.1– 3.0	77	17	6
Part 1, Sept. 13–Oct. 4	4	85,000	97,000	25 ppm.	22 ppm.	19.1–17.8	60	30	10
Part 2, Nov. 9–Nov. 29	4	86,000	111,000	86 ppm.	25 ppm.	8.3– 3.0	94	4	2

The autumn pulse of 1940 was small, irregular, and extended from September 13 to November 29. It actually occurred as two pulses, the first extending from September 13 to October 4 and the second from November 4 to November 29. These two periods were separated by three weeks, during which time the phytoplankton did not exceed 34,000 units per liter. Table I summarizes certain features of these two pulses combined, but the present discussion pertains primarily to that portion between September 13 and October 4. This pulse extended over a period of 4 weeks and reached a maximum quantity of 97,000 units per liter in late September. Diatoms composed 60 per cent of this plankton, while green and blue-green algae composed 10 and 30 per cent respectively. Predominant diatoms were *Melosira*, *Stephanodiscus*, and *Cyclotella*, all belonging to the order Centrales. Predominant green algae were *Dictyosphaerium*, *Coelastrum*, and *Pediastrum*, while *Aphanizomenon*, *Oscillatoria*, *Microcystis*, *Chroococcus* and *Merismopedia* were the dominant blue-greens. Average turbidity during this pulse was 25 ppm., and the average for the 6 weeks preceding the pulse was 33 ppm. Thus from June until October the water was relatively turbid and the first phase of the autumn plankton pulse was characterized by a short duration, a small number of plankters per liter, the dominance of diatoms, and a comparatively high percentage of greens and blue-greens. This first phase of the autumn pulse is compared with the second phase in Table I.

Comparison of the present phytoplankton data with similar data from other parts of Lake Erie or from others of the Great Lakes offers certain difficulties. Several phytoplankton investigations of Lake Erie and Lake Michigan have been made, but in most instances these studies were either not quantitative or they were limited to 6 months or less. Three noteworthy exceptions to this are the studies of Daily (1938) and of Damann (1940) both on Lake Michigan, and the work of Gottschall and Jennings (1933) on Lake Erie near Erie, Pennsylvania, all three of which were year-round studies. These studies reported: (1) the occurrence of spring and autumn pulses both of which were dominated by diatoms, (2) that the predominate diatoms were *Asterionella*, *Fragilaria*, *Melosira*, *Tabellaria*, *Synedra*, and *Cyclotella*, and (3) that greens and blue-greens were most abundant from June to October. Daily (1938) reported that turbidity fluctuated from week to week due to weather conditions, but it displayed two maxima which were caused by the spring and autumn late turnovers. Each plankton pulse was preceded by increases in turbidity which he interpreted as supporting Pearsall's theory (1923) of diatom periodicity. Damann (1940) who continued the work of Daily on Lake Michigan, found a close parallelism between his own data for 1938–39 and the data for 1937–38 by Daily. One conspicuous difference occurred and that was a greater abundance of *Synedra* during the spring of 1939 than during the spring of 1938. He states, "From evidence now at hand it appears that each genus has high and low productive years which in turn have a pronounced effect upon the total yield of phytoplankton for any one year." Data from western Lake Erie confirm this statement. Gottschall and Jennings (1933), whose study extended over a period of 22 months, found marked diffe ences in size and composition of the two late summer and autumn plankton pulses. Unfortunately no data on turbidity were presented in their report. It appears from the above statements that the composition of phytoplankton pulses of western Lake Erie is quite similar to those reported from eastern Lake Erie and Lake Michigan. However, the pulses differ from each other in respect to time of occurrence and size.

The limnological studies of western Lake Erie by Wright and Tidd (1933), although limited to 6 or 7 months, was conducted in the same general region and the same methods were used as in the present investigation. They reported that the average abundance of phytoplankton groups, in thousands of units per liter, for the period late May to early October, 1929 and 1930, was as follows: diatoms, 90; greens, 38; and blue-greens, 58. For the same period in 1939 the writer's results were: diatoms, 76; greens, 20; and blue-greens, 63. In 1940 they were: diatoms, 30; greens, 6; and blue-greens, 10. These data for 1929, 1930, and 1939 are quite similar, but a marked difference exists between the years 1939 and 1940. Turbidity from late May to early October, 1939, was consistently lower than it was for the same period in 1940. These data support the writer's contention that composition and size of phytoplankton populations in western Lake Erie are affected by the degree of turbidity.

At the termination of the second year of study of phytoplankton and its relation to certain physical-chemical factors in western Lake Erie, certain trends become apparent. It is evident that from year to year the time of occurrence, size, duration and composition of phytoplankton pulses vary considerably. Likewise, physical-chemical environmental factors of the water vary, and some of these variations indicate a direct relationship to phytoplankton trends. Turbidity showed a greater fluctuation than any other factor investigated, and for this reason considerable attention has been given to the variation of turbidity during and immediately preceding the plankton pulses. A study of light penetration and turbidity during the present year (Chandler, 1942) shows that 1 per cent of the surface light may penetrate to a depth of less than 2 m. when turbidity is 60 ppm. or higher, and it may penetrate to depths of 9 m. or more when turbidity does not exceed 5 ppm. It becomes apparent from these data that light penetration is drastically reduced in the waters of western Lake Erie when turbidity is relatively high, all of which suggests that the photosynthetic processes of phytoplankton may at times be limited to the upper few meters of water, Unfortunately, light penetration studies were not made from September. 1938, to September, 1939; consequently, the two years under consideration can not be compared in this respect. However, turbidity was measured both years and a comparison of these data with plankton data is made in Table I.

In an attempt to summarize certain results derived from year-round studies of phytoplankton from September, 1938, to November, 1940, Table I has been constructed. This table includes general data pertaining to time of occurrence, duration, size, and composition of phytoplankton pulses, and data on turbidity and water temperature. These two physical factors have been selected from the numerous factors investigated because they showed the greatest variation during pulses in these two years. In Table I a plankton pulse has been arbitrarily limited to quantities exceeding 50,000 units per liter. This quantity has been chosen because when it is reached, subsequent to the summer and winter levels, a definite increase in the phytoplankton occurs. The reason for considering turbidity preceding a pulse, in this table, is because the writer believes that conditions antecedent to the time of a pulse may greatly influence the nature of the pulse. The time interval of 3 weeks is an arbitrary selection to which no significance should be attached.

Data in Table I suggest that low turbidity preceding and during an autumn pulse results in a pulse with the following characteristics: (1) long duration, (2) high average quantity of phytoplankton per liter, (3) relatively high maximum, (4) comparatively low percentage of diatoms, (5) comparatively high percentage of greens and blue-greens. These characteristics are representative of the data for the autumn pulse of 1939. Likewise, when turbidity preceding and during an autumn pulse is high that pulse is characterized by: (1) relatively short duration, (2) low average quantity of plankters per liter, (3) may be high or low maximum, (4) high percentage of diatoms, (5) low percentage of greens and blue-greens. These characteristics are representative of the data for the autumn pulses of 1938 and 1940. It appears that high turbidity during or preceding a pulse does not necessarily result in a low maximum for that particular pulse. In the autumn of 1938 turbidity preceding and during the pulse was 30 ppm., yet a high maximum, 330,000 units per liter, occurred. However, 251,000 (more than 75 per cent) of the 330,000 units per liter consisted of *Stephanodiscus*. This genus was abundant for only a short time in the autumn of 1938 and since then it has not appeared in quantities exceeding 34,000 units per liter. It is of interest to note that this quantity of 34,000 units per liter occurred during the autumn of 1940 when turbidity was 30 ppm. Exclusive of *Stephanodiscus* the autumn pulse of 1938 was even smaller than the autumn pulse of 1940. It is possible that during highly turbid conditions only certain diatoms thrive while other plankters barely exist. *Cyclotella*, a form closely related to *Stephanodiscus*, was more abundant in the autumns of 1938 and 1940 than in 1939; this suggests that relatively high turbidity favors its abundance.

If water temperature bears a specific relation to autumn pulses it is not evident from data collected thus far. In general the water temperature cycle in western Lake Erie was about the same for the two years under consideration. Any differences in water temperature during the three autumn pulses were due to differences in time of occurrence and duration of pulses and not due to differences in temperature for corresponding times of different years.

Data pertaining to spring phytoplankton populations (Table I) suggest that low turbidity preceding and during a pulse results in a pulse of long duration with a relatively high maximum. This is illustrated by the spring pulse of 1940. If high turbidity precedes and prevails during a spring pulse the pulse will be of short duration and its maximum will be relatively low. These characteristics are representative of the spring of 1939. It appears that spring pulses are composed primarily of diatoms regardless of the variations in temperature and turbidity, but the relative abundance of different genera vary from year to year. In the spring of 1939, *Asterionella* was the dominant genus and it reached a maximum of 157,000 units per liter, while *Synedra* ranked second in abundance with a maximum of 48,000 units per liter. In the spring of 1940, *Synedra* was dominant with a maximum of 202,000 units per liter, while *Asterionella* ranked second with a maximum of 108,000 units per liter. Water temperatures were considerably different during the spring pulses of 1939 and 1940, because the two pulses did not occur at corresponding times in the two years. All but the declining portion of the spring pulse of 1939 occurred under an ice-cover, while in 1940 the pulse began under the ice-cover but most of it occurred after the ice had disappeared. It is possible that the differences in turbidity and temperature during these spring pulses may have affected their size, duration and the relative abundance of different genera of diatoms, but it is not clear how these factors are related to the difference in time of occurrence of the two pulses.

A comparison of spring and autumn phytoplankton pulses in western Lake Erie, based on data in Table I, shows the following: (1) duration of spring pulses vary from 6 to 11 weeks, while autumn pulses vary from 8 to 16 weeks; (2) diatoms invariably compose the major portion of the spring pulses, while autumn pulses may be dominated one year by diatoms and the next year by greens and blue-greens; (3) both spring and autumn pulses vary considerably from year to year in respect to time of occurrence.

In the foregoing discussion certain relationships existing between phytoplankton pulses and turbidity in western Lake Erie have been pointed out. Turbidity alone probably has little effect on phytoplankters unless it be through mechanical injury, sedimentation, or the coating of individuals by sediments, and none of these are known to occur in western Lake Erie. The importance of turbidity as a factor influencing phytoplankton populations probably lies in its relation to light penetration. Light studies (Chandler, 1942) in this particular region show that turbidity greatly reduces the intensity of light at various depths, consequently the higher the turbidity the lower the intensity of light at a given depth. Thus it might be expected that this reduction in intensity of light would alter the rate of photosynthesis by phytoplankters at various depths. A recent study by Meyer and Heritage (1941) shows that when water in this region becomes highly turbid the rate of apparent photosynthesis in *Ceratophyllum demersum* is greatly reduced even at depths of 1 m. and less. Their data also show that the compensation point for this species varied from a depth of 10 m. when turbidity was near its summer minimum to a depth of 2 m. when turbidity was near its summer maximum. Unfortunately we do not have comparable data on the depths at which compensation points occur for plankton algae of this region; however, it is likely that the rate of photosynthesis of plankton algae follows the general trends shown by *Ceratophyllum demersum*. If this is true, then highly turbid conditions preceding a phytoplankton pulse might reduce the rate of photosynthesis of algae to such an extent that the quantity of phytoplankton would not reach pulse proportions for some time even though other conditions favored it. Likewise, high turbidity during a pulse may tend to retard growth and reproduction of algae to such a degree that the pulse will be small and of short duration. If suspended materials in water have a selective effect on light penetration, then certain light rays will be present in greater intensities, at a given depth, than other light rays. If this does occur, then those algae best adapted for the utilization of this selected light will thrive while others will be present in small quantities if not absent. This might be a factor in producing differences in composition of phytoplankton pulses for the same season of different years.

The writer does not believe that the variations of phytoplankton populations from year to year in western Lake Erie can be explained entirely on the basis of light and its relation to photosynthesis, but there is evidence that the reduction of light through the effects of high turbidity may be a limiting factor at times. In arriving at an explanation of the variations of phytoplankton pulses in respect to time of occurrence, duration, size, and composition, the following factors also must be considered: (1) annual and seasonal amounts of solar radiation delivered to the surface of the lake, (2) variation in quality and quantity of dissolved substances in the water, (3) size, function, and activity of the bacterial population, and (4) competition among plankters for food and space. Projects are under way at this laboratory to investigate the first three factors listed.

Summary

1. Year-round limnological data based on weekly observations of phytoplankton and general physical-chemical factors of western Lake Erie are presented.

2. General physical-chemical factors, exclusive of turbidity and ice-cover, were quite similar to those for corresponding times of the preceding year.

3. The ice-cover of 1940 was thicker and it covered a much larger portion of the western end of Lake Erie than it did the preceding year.

4. Turbidity varied from 5 to 60 ppm.; the water was most turbid in summer and autumn, and it was least turbid in winter and spring. In the preceding year turbidity was highest in spring and autumn and lowest in winter and summer.

5. The spring phytoplankton pulse, with a maximum of 374,000 units per liter, occurred from March 14, to May 28, 1940. Diatoms composed about 98 per cent of this pulse and the genera most abundant were *Synedra*, *Asterionella*, *Fragilaria*, *Tabellaria*, and *Melosira*.

6. The autumn pulse occurred in two parts, separated by three weeks. Diatoms composed 77 per cent of this entire pulse and the genera most abundant were *Melosira*, *Stephanodiscus*, and *Cyclotella*.

7. Green and blue-green algae together composed 23 per cent of the entire autumn pulse and about 2 per cent of the spring pulse.

8. Data based on weekly observations indicate that when the average turbidity of the water of western Lake Erie is 25 ppm. or greater preceding and during a phytoplankton pulse, the pulse is small and of short duration. Likewise, when the average turbidity is less than 20 ppm. preceding and during a pulse the pulse is large and of long duration. Diatoms compose a greater percentage of the total phytoplankton when the average turbidity exceeds 25 ppm. than when it is less than 20 ppm. Conversely, green and blue-green algae compose a greater percentage of the total phytoplankton when the average turbidity is less than 20 ppm. than when it is greater than 25 ppm.

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